Chapter 3

Low-Dimensional Materials for Disruptive Microwave Antennas Design

Charlotte Tripon-Canseliet and Jean Chazelas

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.79514

Abstract

This chapter is devoted to a complete analysis of remarkable electromagnetic properties of nanomaterials suitable for antenna design miniaturization. After a review of state of the art mesoscopic scale modeling tools and characterization techniques in microwave domain, new approaches based on wideband material parameters identification (complex permittivity and conductivity) will be described from impedance equivalence formulation achievement by de-embedding techniques applicable in integrated technology or in free space. A focus on performances of 1D materials such as vertically aligned multi-wall carbon nanotube (VA-MWCNT) bundles, from theory to technology, will be presented as a disruptive demonstration for defense and civil applications as in radar systems.

Keywords: nanotechnology, electromagnetism, multiscale modeling, 3D full-wave analysis

1. Introduction: miniaturization challenges in microwave domain

Material band gap engineering opens new avenues for the optical control of these new nanomaterials and achieves a drastic miniaturization degree for wideband frequency devices. Electronics and optoelectronics applications, based on materials with a bandgap in the band structure, would require combinations of atomically thin two-dimensional (2D) semiconductors in hybrid devices. The feasibility of separating and even synthesizing atomically thin layers of MoS2, MoSe2, WSe2 and WS2 has been demonstrated, and this offers new perspectives for the development of electronics and optoelectronics based on atomically thin films. This research area relies on the investigation of atomically thin two-dimensional (2D) systems, including growth and studies of atomically thin 2D crystals beyond graphene; investigation of their electronic and optical properties; development of applications of hybrid systems in functional device; and growth and preparation of new layered systems for spintronics. By reducing the dimensionality of materials, a new class of devices could be foreseen which are ultra-thin (nanometers), ultra-light, flexible, wearable, bendable and energy harvesting.

This emerging research area deals with technological breakthroughs benefits from quantum effects exaltation by the use of nanomaterials/nanotechnologies in the definition and description of next future electromagnetic (EM) nanosystems. This area addresses and brings responses to the main challenges in the design of future EM systems such as: (1) how quantum effects will improve the performances of EM systems; (2) how to design an EM system based on nanomaterials; (3) how to control or reconfigure a system based on nanomaterials; and (4) how to define and design an EM nanosystem.

Emerging nanotechnologies dedicated to 1D and 2D materials processing offer today the possibility of design innovations in broadband reconfigurable EM systems. By enabling exceptional electromagnetic material properties, high degree of confinement of electromagnetic waves, near field coupling access and drastic miniaturization.

Material engineering starts from energy band profile study, which legislates excitonic energy transfers allowing charge carriers transport. Since decades, conventional electronics and optoelectronics components benefits from well-known bulk semiconducting materials properties in which carriers can easily diffuse in three dimensions following parabolic band profiles. By eliminating progressively one spatial dimension, energy transfer possibilities become more and more confined as they are governed by sharp transitions sustained by step or Dirac band profile, such as in 2D, 1D or 0D materials. Furthermore, monoatomic layer materials defined by atoms arrangement witness even more in-plane anisotropic properties from nonsymmetrical lattice configuration or chirality. From these statements, majority carriers diffusion and transport optimization are under study by surface functionalization techniques and heterostructures process elaboration.

Today, it becomes obvious that by promoting the confinement of electromagnetic interactions new electronic and optoelectronic devices design optimizations will move toward the definition of 2D structures supporting surface wave propagation.

2. Carbon-based materials as promising low-dimensional materials technologies for electronic systems

Low-dimensional materials belong to a new class of materials in which space confinement appears in one or two dimensions. Carbon-based materials such as graphene and SW/MW CNTs represent the most mature material family in nanotechnologies that could strongly alleviate the silicon technology limits compared to alternative approaches such as Si-Ge and III-V high mobility semiconductors, with particular emphasis on their possible applications in microwave and mmm wave electronics.

Indeed, the extraordinary mechanical and electrical properties of CNTs make them ideal candidates as building blocks for RF ICs. They can be metallic or semiconducting depending on their chirality. The high conductivity of single-wall metallic nanotubes (SWNT) or multi-wall nanotubes (MWNT) allows for designing simple actuation systems based on the direct electrostatic coupling with metallic gates. These properties make them particularly suitable for both basic building blocks of active components as well as electrical interconnects.

Graphene has emerged as a promising material for electronics in the last years. It is chemically and thermally one of the most robust materials available. Furthermore, it has proven potential for ultra-high frequency electronics. In less than 6 years from the material discovery by A. Geim and K. Novoselov, and despite the remaining technological issues still under heavy development, scientist has managed to provide proof of concept active devices (FETs) operating at frequency comparable to the state of the art. Especially for wireless applications, an important factor is that graphene microwave devices can be easily accommodated to the standard 50 W impedance. Additionally, the nonlinear behavior of the I-V dependence of graphene contacted with metals can be used to multiply or detect RF signals. Moreover, graphene growth is rapidly progressing from a purely scientific field into the world of applications (**Tables 1** and **2**).

2.1. Single- and multi-walled carbon nanotubes (SW/MWCNT) as 1D materials candidates

The main growth techniques recently studied concern in-situ growth by CVD/PECVD or dispersed solutions or external deposition techniques on substrate by the use of dielectrophoresis (DEP) and droplet techniques.

Parameter	Values and units	Observations
Diameter Length	1 to tens of nm μm to mm and even cm	The best electron emitters ever known
Current density	> 10^9 A/cm^2	Highest current density of any material
Thermal conductivity	6,600 W/mK	More thermally conductive than most crystals
Young modulus	1 TPa	Among the stiffest materials
Mobility	10,000-50,000 cm^{2}V^{-1}s^{-1}	Simulations: mobilities beyond 100,000 cm^{2}V^{-1}s^{-1}
Mean free path (ballistic transport)	0.3-1.2 μm in semiconducting CNT 1-3 μm in metallic CNT	Measured at room temperature At least three times larger than in semiconducting heterostructures
Conductance in ballistic transport	$G = 2\times(2e^2/h) = 155$ μS	$1/G = 6.5$ kΩ

Table 1. Summary of CNT properties.

Parameter	Values and units	Observations
Mobility	40 000 $cm^2V^{-1}s^{-1}$	At room temperature (intrinsic mobility 200 000 $cm^2V^{-1}s^{-1}$ in suspended structures)
Mean free path (ballistic transport)	200- 400 nm	At room temperature
Fermi velocity	c/300=1000000 m/s	At room temperature
Thermal conductivity	5000 W/mK	Better thermal conductivity than in most crystals
Young modulus	1.5 TPa	Ten times greater than in steel

Table 2. Summary of graphene properties.

Carbon nanotubes (CNTs) are molecular-scale tubes of graphitic carbon and can be considered as the stiffest and strongest fibers known and have remarkable electronic properties and many other unique characteristics. In many applications such as field emission sources, biosensors, electrical interconnects and micromechanical devices, it is necessary to grow CNTs vertically aligned on the substrates. This alignment in the vertical direction can be achieved through these two methods: thermal CVD (TCVD) and plasma enhanced CVD (PECVD). The alignment in TCVD is achieved by crowding effect from neighboring CNTs [1]. For building a waveguide antenna, CNT bundles have been proposed to mitigate the problem of impedance mismatch by adjusting different tube diameter, length and bundle cross-section size. The exact positioning of the nanotubes is also vital for applications such as RF filters and micro switches. Uniform and vertically aligned CNTs of desired sizes can be grown at precisely determined locations by the process of PECVD [2, 3]. The PECVD method has the advantage of being controllable with tube diameter and length less than 5% deviation. For nano electromechanical devices, a good contact to the underlying metal electrode is essential [4]. The optimum condition of catalyst and metal underlayer can be tailored and controlled. According to the growth of vertically aligned carbon nanotubes, state of the art in **Figure 1** shows the CNT arrays on the Si substrate.

2.2. Graphene as 2D materials candidate

Synthesis and scalability of 2D layered materials is one of the most competitive challenges in the material science research area. The first well-known technique of process by mechanical exfoliation discovered by A. Geim for remarkable graphene delivering the best material properties has faced limitations in terms of needs of complementary steps for material encapsulation to guarantee a minimum air and humidity stability. Today, some scalable manufacturing

http://dx.doi.org/10.5772/intechopen.79514

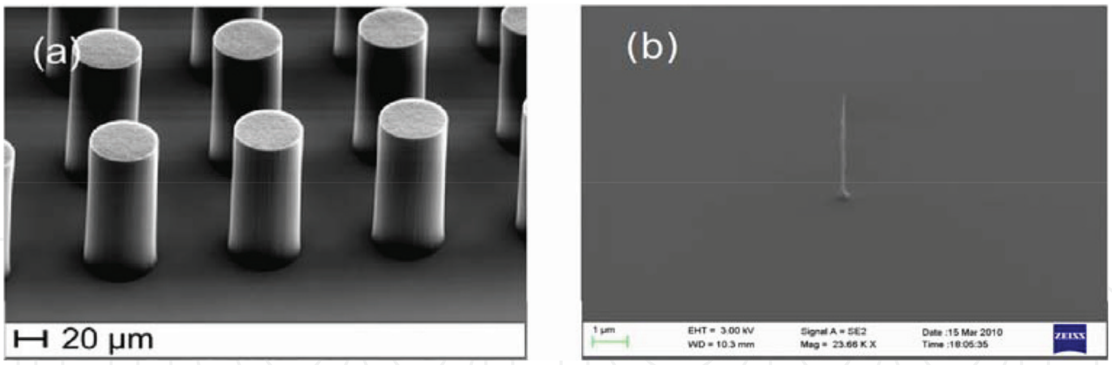

Figure 1. (a) CNT bundles grown by TCVD and (b) single CNTs grown by PECVD.

processes are identified to help in large-scale development of graphene/CNT-based devices and system development.

In the area of solution-based synthesis, solvent-based exfoliation methods have been recently demonstrated for mono and few layer nanosheets fabrications, with efforts brought to solvent toxicity elimination thanks to the use of water [Casigari]. In association, emerging ink-jet printing techniques become promising for large-scale synthesis of 2D materials. Structural imperfections may occur locally compared to other approaches but more adequate for low-end electronics applications, as technological key for large-scale material heterostructures ordering on flexible substrates.

Molecular beam epitaxy (MBE) growth technique, mainly used for bulk semiconducting materials manufacturing still remains one of the most controlled technique for highly precise thickness management with high level of material quality, with availability of in-situ material characterization during process.

In the area of vapor-based synthesis, metalorganic chemical and physical vapor deposition (MOCVD), as well as atomic layer deposition (ALD) approaches are proposed for TMD materials synthesis avoiding any catalyst layer presence for growth in some cases.

2.3. Material integration in electronic devices: scaling electrical contacts

In order to benefit from exceptional electromagnetic properties of nanomaterials in microwave domain, crucial intrinsic impedance considerations may be studied to maximize electrical signal transmission. For this aspect, material Fermi level location knowledge is crucial, and must be subsequently confronted to the working function of selected noble metals to be used as electrodes such as Au, Ti, Ag, Fe and Pd as the most common examples. Depending on the spatial constitution of materials, different approaches can be employed to optimize electrons and holes flows and recombination processes, that is, charged injection electronic devices.

The second aspect to be considered concern the skin depth effect which occurs in any metal and imposes material thickness constraints for electrical ohmic losses minimization, as a function of frequency and material conductivity. In the case of low-dimensional materials, where at least one dimension of material is atomically thin, unprecedent behavior with frequency is expected.

With the decrease of the dimensions of electronic devices, the role played by electrical contacts is ever increasing, eventually coming to dominate the overall device volume and total resistance. This is especially problematic for monolayers of semiconducting transition-metal dichalcogenides (TMDs), which are promising candidates for atomically thin electronics. Ideal electrical contacts to them would require the use of similarly thin electrode materials while maintaining low contact resistances.

As reproduced in **Figure 2**, 2D material heterostructure constitution for a complementary matching process or a specific choice of metal may be needed to form an alloy avoiding Van der Walls gap naturally imposed by some 2D materials in contact with noble metals, by orbital overlapping lack [5].

Recently, valley dynamics of excitons in semimetals are taken under considerations for semimetals. Tunnel barrier introduction at electrical contacts assumed by ferromagnetic electrodes has been investigated in order to modulate the contact resistance of graphene and TMDSs with electrodes by spin injection, allowing impedance matching by magnetoresistance signal detection.

Main considerations for charge transfer maximization are focused also on contact transfer length L_T, which defines the length over which injection occurs from the contact edge, defining then the contact resistance R_c as [6, 7].

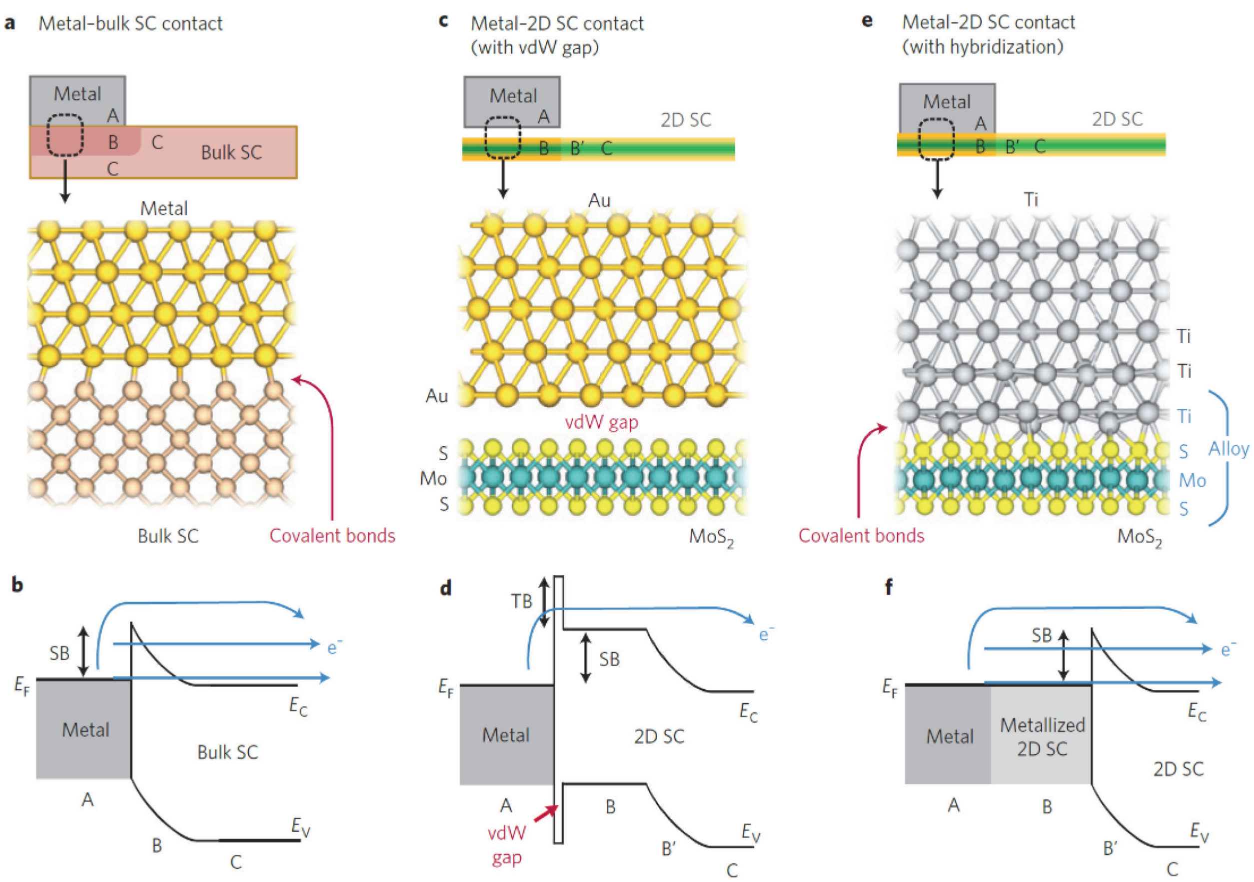

Figure 2. Different types of metal-SC junctions and their respective band diagrams for (a, b) bulk interface, (c, d) metal/2D SC interface lik MoS2/au contact, (e, f) hybridization of metal/2D SC interface [6].

$$R_c = \sqrt{\rho_c.R_s}\,\mathrm{cotanh}\left(\frac{L}{L_T}\right)/L_W \tag{1}$$

With

$$L_T = \sqrt{\frac{\rho_c}{R_s}} \tag{2}$$

where L is the length and Lw is the width of the contact, ρ_c is the nanomaterial resistivity and Rs is the metal-material interface resistivity. It can be seen that the dependence of Rc on L is nonlinear because of current crowding.

2.4. Latest study-case examples

2.4.1. CNT-based transistors

Carbon nanotube (CNT) field effect transistors (FETs) are under investigation as replacements for silicon and III-V high-speed electronics [8]. Semiconducting CNTs are unique electronic materials with room temperature carrier mobility in excess of 100,000 $cm^2/V/s$, three times larger than that of InAs, and a band gap of -0.9 eV, which is close to that of Silicon. Some of the key semiconducting properties of CNTs are compared with other materials in **Table 3** [9]. The high mobility makes CNT FETs attractive for low-power amplifiers and the high-saturated electron velocity leads to projected operation into the THz range [10]. Single-wall nanotubes (SWNTs) are inherently small, ~nm in diameter. This ultra-small diameter enables effectively one-dimensional conduction with the potential for ultra-low shot-noise performance and improved linearity. An additional benefit of small size is extremely low capacitance, which translates into high operating speeds without the need for extreme lithography.

CNT FETs based on SWNTs have been extensively characterized at DC. Much of this attention has been motivated by the near ballistic conduction, high current and transconductance density of CNT transistors [11]. But their high-frequency application faces a challenge of impedance matching due to the inherent mismatch between the resistance quantum (~ 25 kΩ) typical

	Bandgap eV	Electron mobility $cm^2/V/s$	Saturated electron velocity 10^7 cm/s	Thermal conductivity W/cm/K
CNT	0.9	100,000	>10	>30
InAs	0.36	33,000	0.04	0.27
Silicon	1.1	1500	0.3	1.5
GaAs	1.42	8500	0.4	0.5
InP	1.35	5400	0.5	0.7
4H-SiC	3.26	700	2	4.5
GaN	3.49	900	3.3	20

Table 3. Electrical properties of material for FETs.

of nanodevices and the characteristic impedance of RF circuits (50 Ω). There are only a few reports on HF performances measurement of CNT transistors. In terms of cut-off frequency, Purdue University measured f t = 2.5 GHz (intrinsic value) [12], NEC research laboratory measured f_t = 10 GHz (intrinsic value) [13]. The state of the art is the direct measurement of a current gain cut-off frequency of 4 GHz and an intrinsic value of 30 GHz (calculation by removing access and parasitics capacitances) on a transistor composed of a large number of CNTs [14]. Nevertheless, a large part of the deposited CNTs is metallic and this prevents transistor operation at higher microwave frequencies. CNT FET technology can potentially improve in comparison to that of a scaled silicon technology. As a quasi-one-dimensional (1D) conductor, a CNT channel resistance is limited by the fundamental quantum resistance (R Q) of 6.5 kΩ per tube. The simplest idea is to deliver to this quantum resistance (ignoring metallic versus semiconducting behavior) a 1 V operating voltage, which will give a current of about 150 μA/nanotube. With all its non-idealities like poor contacts, scattering as well as existence of tunneling barriers, the state of the art CNT FETs can deliver around 20 μA/nanotube at ~1 V.

Moreover, the capacitance per nanotube is ~2–5 aF, which corresponds to ~1 fF/μm, not far from a silicon transistor. The conclusion is that the 1D CNT array technology can potentially deliver a much higher current in the same area and for identical gate capacitance, which will lead to increased current density and lower delay at higher integration density. It can be also concluded that an arrayed CNT FET using the same interconnect parasitics, as the most advanced 65 nm CNT transistor will feature an 8-times area improvement and 5-times delay reduction [15]. To verify performance at microwave frequencies, Pesetski et al. [16] proposed to develop an alternate measurement technique: instead of observing the output at the input frequency, which was susceptible to crosstalk, they performed a two-tone measurement and observed the intermodulation products. As a result, the CNT FET acts like a mixer, producing an intermodulation product at 10 kHz; and no evidence of a roll-off caused by the CNT FET was observed, even at 23 GHz.

2.4.2. Graphene-based transistors

Transition-metal dichalcogenides have developed important visibility [17] in the recent years due to advances in nanotechnology. Several potential applications [18] are well suited for TMDCs among which they are also interesting for transistor applications. Regarding high-frequency transistors, not a lot of results are published mainly due to lack of large area material, the best results were obtained using a MoS_2-based channel with a thickness of few monolayers. The channel length was 1 μm, whereas the backgate capacitance was 11.5 nF/cm^2. The mobility reported was 170 cm^2/Vs for a drain voltage of 0.5 V and a backgate voltage of 20 V. The MoS_2 thickness is critical for high performance FET transistors. The thickness considered [19] is in the range 2–7 nm. Reducing the dimensions of the channel length to 116 nm, the FETs showed a transconductance of 60 μS/μm at a drain voltage of 5 V and a drain conductance of less than 2 μS/μm, indicating an intrinsic gain of 30 with an on–off ratio higher than 10^7. The cut-off frequency was 42 GHz and the maximum oscillation frequency was 50 GHz. Even though technology is still at its early stages [20], TMDS-based devices already exhibit good metrics, comparable or even higher to those achieved by graphene.

2.4.3. CNT-based interconnects

As previously mentioned, 3D IC technology is one of the main driving forces for the continuous down scaling of the IC device [21, 22]. There are many interconnection technologies such as wire bonding, edge connect and capacitive or inductive coupling method to fabricate 3D-IC devices [23, 24]. However, the most key technology for enabling 3D-IC package is through-silicon via (TSV) technology which acts as paths for signal exchange and power delivery between the stacked chips [25, 26]. TSV technology has allowed great progress in reducing signal delay, enhancing the IC integration and decreasing the overall packaging volume [27]. Thus, the development of this technology is accelerating the miniaturization of 3D-IC devices as well as integration of I/O systems. The key performance of TSVs is determined by the filling materials used in the silicon via. There are various materials that have been used for the TSV, such as tungsten (W), copper (CU) [28, 29] and a Ag/polypyrrole composites [30]. The copper is the most commonly used filling material for TSV due to its excellent electrical conductivity and low process costs. However, the main limiting factor for Cu-TSV technology is the large difference in the coefficient of thermal expansion (CTE) between Cu and Si, which results in mechanical stress in the TSV and the surrounding Si [31]. In addition, the electro-migration and skin effects also limit the application of Cu TSV in high-frequency applications [32]. However, it is currently not technologically possible to use Cu for high aspect ratio via structures [33].

A series of modeling work on CNT interconnects has been done by Naeemi and Meindl [34]. The modeling of the capacitance and inductance components of CNT interconnects can be found in [35]. A high-frequency analysis of CNT interconnects has also been performed [36], in which one interesting conclusion is that the skin effect of CNT interconnects is significantly less severe than that of metal lines. Based on the model described in the reference listed above, the resistances of CNT off-chip interconnects, such as through-silicon-vias (TSVs), can be estimated by straightforward calculations assuming some typical dimensions. An MWNT with 30 nm outer diameter and 15 nm inner diameter, 100 μm length and 1 μm electron mean free path, at room temperature has a conductance of 0.048 $k\Omega^{-1}$. This leads to an estimated resistance of 21 kΩ for such an MWNT if all its walls can be contacted. Note that here the electron mean free path is taken as 1 μm based on experimental observations. Therefore, if a loosely packed CNT forest can be densified into closely packed bundle, the conductivity of such a structure can be greatly increased [37].

3. Exceptional electromagnetic material properties for microwave applications

Effective theoretical frequency-dependent material conductivity of carbon-based nanomaterials: from individual to collective (bundle) configuration.

Frequency-dependent graphene conductivity can be approximated using Kubo formula.

$$\begin{aligned}\sigma_s(\omega) &= \mathrm{i}\frac{1}{\pi\hbar^2}\frac{e^2 k_B T}{\omega+\mathrm{i}2\Gamma}\left\{\frac{\mu_c}{k_B T}+2\ln\left[\exp\left(-\frac{\mu_c}{k_B T}\right)+1\right]\right\}\\ &\quad+\mathrm{i}\frac{e^2}{4\pi\hbar}\ln\left[\frac{2|\mu_c|-\hbar(\omega+\mathrm{i}2\Gamma)}{2|\mu_c|+\hbar(\omega+\mathrm{i}2\Gamma)}\right]\end{aligned} \tag{3}$$

with the chemical potential μ_c and the relaxation rate Γ. This complex expression in which Γ has been experimentally calculated to 0.1 meV, demonstrates a complex behavior with σ_{real} and σ_{imag} as real and imaginary parts of $\sigma_s(\omega)$ depending on value μ_c. From a dyadic Green's function formulation of electromagnetic fields propagation through Sommerfeld integrals, TE or TM mode surface wave propagation operation has been validated whether positive or negative value of σ_{imag} [38].

3.1. SW/MWCNT conductivity

Individual SW CNT consist in a spatial unique angled-rolling of a graphene sheet depending on the associated chiral vector which defines their metallicity degree.

Starting from graphene conductivity formulation above, armchair and zigzag enrollment configuration leading to a metallic behavior implies also a complex conductivity definition in which imaginary part existence can be detected (see **Figure 3**).

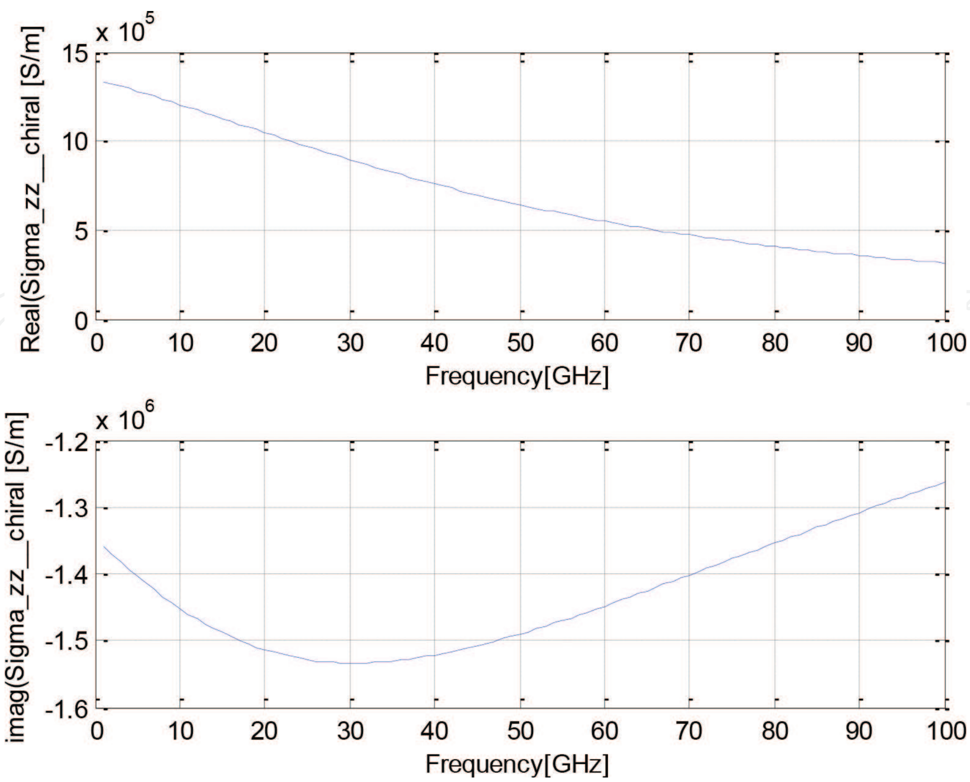

Figure 3. Dynamic conductivity as a function of frequency of a metallic chiral CNT.

$$\sigma_{zz_{chiral}} = -j\frac{8\pi e^2\gamma_0\sqrt{3}}{h^2\sqrt{m^2 + n^2(\omega - j\nu) + mn}} \text{ with } 2m + n = 3N \tag{4}$$

(m and n equal to 1)

As a consequence, for SW CNT, an equivalence must be inserted between the surface conductivity of a cylinder and the conductivity of a material with a dependency on 1/r, where r is the radius of the CNT cylinder, for the definition of the material impedance, which still remains a complex expression.

For MW CNT, the conductivity appears as a sum of individual density current of each wall.

3.2. State of the art microwave material modeling techniques

3.2.1. 1D materials: individual SW and MW CNT

In 2007, first modeling tools of these 1D nanomaterials were developed for optical scattering predictions of metallic SWCNTs array by Hao and Hanson [39] by using periodic Green's function applied to an array of finite-length conducting elements with quantum conductance given previously. At the same time, Maksimenko [40] defined a competitive electromagnetic approach based on Leontovich-Levin Integral Eqs. (IE) method. First surface impedance model of CNT appeared in 2008 from Fichtner by using Hallens'type IE with a modified Kernel function in equations. Electromagnetic modeling work for infinite objects was pursed by Berres and Hanson in 2011 in the microwave and IR frequency regime using a semi-classical approach [41]. For bindle-type configuration of arrays of MWCNT, resulting global conductivity calculation was adopted by Choï and Saranbandi. In this last case, Method of Moments (MoM) and the Mixed Potential Integral Equation (MPIE) were implemented to predict CNT-based strip antennas and thin gold films [42].

3.3. State of the art microwave material characterization techniques

EM material parameters identification at RF/microwave frequencies is a milestone to understand and design new RF components for future implementation in next generation of microwave systems. Principles and techniques of material parameters characterization in microwave domain using transmission lines have been widely studied for determination of bulk material permittivity, permeability and conductivity in frequency domain. Non-destructive method by electromagnetic coupling of unknown material thin layer with a quasi-TEM propagation mode in planar configuration (microstrip or coplanar line) becomes the most appropriate methodology today to achieve a complete and broadband characterization.

3.3.1. Coaxial environment

For nanomaterials characterization, coaxial lines techniques have been mainly used because of direct commercial provision access of 2D/1D materials in disperse solutions. These techniques imply frequency bandwidth limitations because of waveguides dimensions and random material orientation in relation to e-field polarization direction.

3.3.2. Probe-test environment

Device downscaling motivation has progressively opened the route for the development of electromagnetic properties identification at dimensions which must be consistent with operating frequency.

Some research groups involved in ultra-thin layers deposition on reference substrates have re-used former modeling tools dedicated to homogenous material frequency-dependent permittivity identification by conformal mapping technique. In this approach, where a parallel-type capacitance equivalence of any material layer is assumed from permittivity elliptic integrals equations applied to a coplanar line configuration (K and K′), direct extraction of real permittivity of an unknown material layer is reachable if stacked uniformly (i.e., complete layer under/overlying) in plane from signal line to ground planes in a well-known multilayer coplanar structure. Complementary de-embedding structures need to be fabricated in order to eliminate probe-test parasitic on measurement results.

This technique is based on microwave S-parameters measurements of dedicated test beds structures designed in microstrip and coplanar technology. After analytic S-to-ABCD-matrix conversion for the exact determination of effective propagation constant and permittivity of the transverse multilayered structure, frequency relative permittivity of 2D/1D material is obtained as an inverse problem by using a conformal mapping technique from the Veyres-Fouad Hanna approximation assuming multiple layers as a superposition of capacitances. This specific characterization technique in frequency allows experimental detection of anisotropic behavior of nanomaterials thanks to electromagnetic fields orientation access and opens routes to the use of nanotechnology for the definition of new multiscale microwave devices design.

A complementary modeling tool based on a circuit-type approach could have been added to this procedure where equivalent lineic R, L, C values of the studied material are estimated from circuit simulations in commercial softwares. This approach has been performed to graphene flakes, as in Ref. [43].

3.3.3. Free space environment

For antennas and radars systems, an equivalent approach in free space has been implemented by assuming a bi-static experimental configuration for multilayered samples, using a contactless technique avoiding anechoidal environment. This technique is based on reflection coefficient measurement of bulk materials, which imposes self-consistent calibration structures. Thanks to horn antennas electromagnetic excitation, material impedance in both TM and TE modes can be extracted allowing the identification of material permittivity and conductivity with anisotropic behavior checking. Limitation on material thickness reduction is not identified yet because of characterization configuration in reflective manner and dimension to wavelength, and allows broadband materials parameters identification.

A complementary approach is now under study in order to extend bi-static measurements to low-dimensional materials. Technical challenges target characterization technique limitations as compared to material thickness. This approach is assisted by electromagnetic simulations which help in the definition of de-embedding structures, as well as planarity material requirement and material surface constraints. In this way, a 40–67 GHz frequency band has been selected to overcome these boundary conditions allowing access to centimeter-squared surface scale characterization of materials with atomic thickness.

3.4. Material impedance equivalence: toward "Mattertronics"

In order to solve multiscale problem, characterization techniques customization to low-dimensional materials becomes crucial for any device design work by full-wave analysis in which implemented material constitutive parameters from classical electromagnetic material Drude/Lorentz representation and Kramers/Kronig relationships [44] are used for material R, L,C circuit equivalence. Material complex permittivity (ε), conductivity (σ) and permeability (μ) knowledge helps in the definition of material impedance Z equivalence.

4. Application to microwave antenna design: toward subwavelength radiation

4.1. Fundamental antenna parameters requirements: from theory to technology qualification

The simplest representation of a radiating element consists in a LC resonant cell. Wire antennas are the oldest and most versatile antennas suited for various applications. It is a simple device to understand most of the radiation mechanism and the dipole structure simplification of radiating elements. The typical configuration is made up of two conductor wires, with a length of $\lambda/2$.

The current distribution in the conductor wires can be considered in one dimension due to the geometry (usually the z-axis direction). The time variation of the current distribution will generate a radiated electromagnetic field in the surrounding space. Maxwell's equations lead to the relation between the current variation I(z) and the radiated field E_θ in the far field space. Along with the radiation pattern is a set of other key parameters that are used to quantify an antenna and its performances:

- input impedance is the impedance the power input circuit will have to match in order to transmit the maximum power to the radiating device.
- gain is the ratio of intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna was radiated isotropically. The radiation intensity corresponding to the isotropic radiated power is equal to the input power accepted by the antenna divided by 4π.
- directivity is the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity average over all directions.
- The radiation efficiency which is the ratio of the radiated power over the accepted power and is a dimensionless combined factor of both the conduction efficiency (losses through

metal conduction) and dielectric efficiency (losses through propagation in dielectric space) considered in one dimension, due to the geometry (usually the z-axis direction). This is the time variation of the current distribution that will generate a radiated electromagnetic field in the surrounding space. Maxwell's equations lead to the relation between the current variation I(z) and the radiated field E_θ in the far field space.

From material point of view, targeting radiation performances, similar parameters must be strongly considered such as:

- Lineic inductance/capacitance in order to define the efficient dimension of a LC resonant cell
- Dynamic permittivity which allows the definition of plasma resonance frequency
- Band diagram and work function definition in a metallic atomic configuration to identify efficient contact type with microwave electrode access to match input impedance.

4.2. MWCNT bundle-based microwave antenna design case: from theory to experiment demonstration

As main technological challenge relies on experimental material impedance identification in microwave domain, first studies have led to the choice of a differential-type approach. In order to overcome physical constraints imposed by material dimensions access, following technological process, preliminary planar resonant structures in CPW technology have been achieved with suitable taper-based electrodes (**Figure 4**), for which a resonant frequency shift assumed by VA-MWCNT bundle is expected. For microwave signal coupling methodology, different ended geometries have been tested in order to validate the material properties from different devices.

From this approach, the equivalent impedance of VA-MWCNT bundles connected in series to the microwave test bed structure is obtained by direct input impedance subtraction de-embedding techniques.

Preliminary research works have been done on sub-wavelength MWCNT-based antennas design benefiting from natural LC behavior or complex conductivity never achieved in classical conductors in microwave domain. By exploiting also a vertically aligned CNT bundle configuration reducing drastically the contact resistance of individual MWCNT [39], first demonstration of resonance frequency shift of coplanar antennas incorporating a 500 μm-length MW CNT circular bundle have been experimentally revealed at a microwave frequency around 60 GHz (**Figure 4**). In parallel, electromagnetic material properties identification by experimental material complex impedance extraction under TE or TM mode excitation is under progress.

A broadband microwave characterization is performed using a CASCADE MICROTECH probe-test equipment allowing S-parameters measurements with a vectorial network analyzer in the 0.2–67 GHz frequency bandwidth, calibrated by the SOLT method.

From reflection coefficient measurements, input impedance of resonant structure has been extracted. The validity of the measurements requires to apply this methodology away from the resonant frequency band, in order to avoid undefined behavior.

http://dx.doi.org/10.5772/intechopen.79514

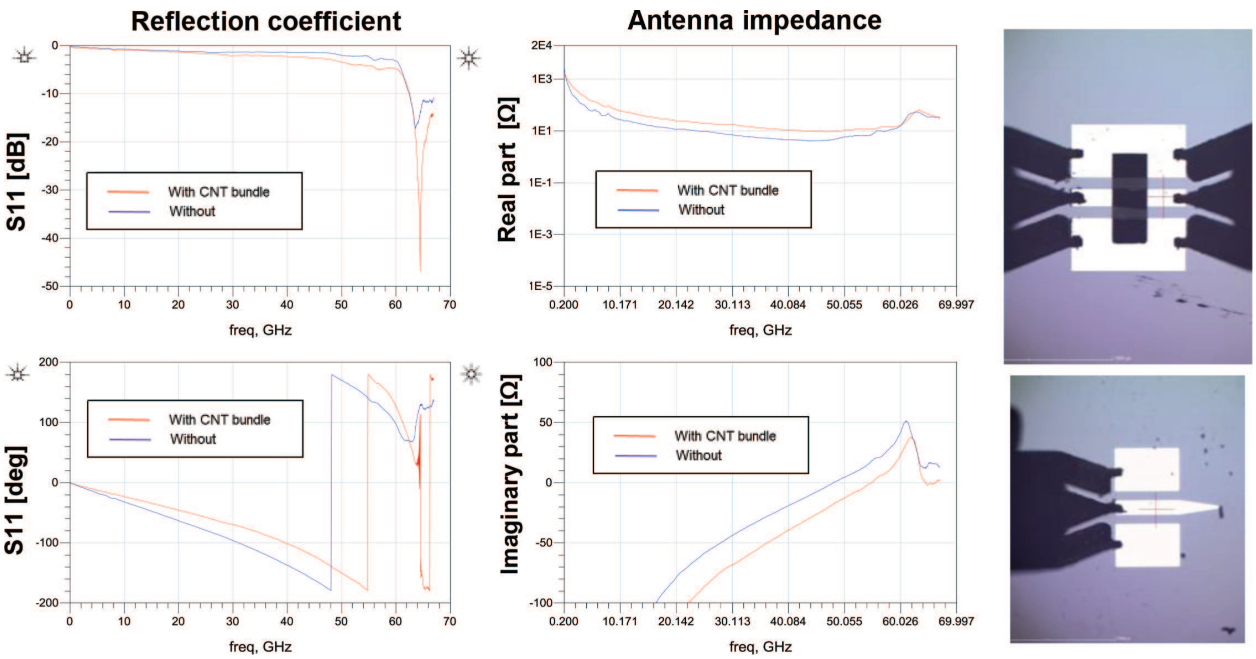

Figure 4. Microwave performances of a MWCNT-based nano antenna in coplanar technology: (a) reflection coefficient in magnitude and phase of device with (red) and without (blue) MW CNT bundle, (b) antenna impedance in real and imaginary part with (red) and without (blue) MW CNT bundle, (c) optical image of MWCNT-based test bed structure–(d) optical image of the MW CNT-based nano antenna.

By adopting a specific de-embedding technique procedure, frequency-dependent CNT bundle impedance extraction in TE and TM mode excitation confirms accessible additional design matching solutions at a frequency of 10 GHz.

Today, by benefitting of technological processes achievement access, 3D electromagnetic modeling parametrization of MW CNT bundles with technology will add complementary degree of freedom in MW CNT-based sub-lambda antenna and array design. On-chip emitting/receiving modules design validation by on-wafer sub-lambda S-parameters measurements (DC-110 GHz) [45] will be assisted by preliminary equivalent electromagnetic material properties experimental validation (ε, μ and σ) fulfilling anisotropic behavior of individual vertically aligned MW CNTs grown in bundle with length-to-diameter aspect ratio dependency comparable to theoretical predictions made for metallic nanowire-based antenna [46], governing MW CNT-based individual sub-lambda antenna design.

5. Conclusions and prospects

This chapter addresses the emerging research area dealing with technological breakthroughs benefitting from quantum effects exaltation by the use of nanomaterials/nanotechnologies in the definition and description of next future electromagnetic (EM) nanosystems.

It is shown that emerging nanotechnologies dedicated to exceptional electromagnetic properties of 1D and 2D materials processing offer today the possibility of design innovations in broadband reconfigurable EM systems with high degree of confinement of electromagnetic waves and extreme miniaturization.

In the field of electromagnetism, the near future will be governed by the merging of three apparently independent domains:

- The first one is dealing with the generation, control and processing of surface waves
- The second one is associated to the merging area of antennas based on nano-radiating elements and nanoantennas
- The third one is covering the ever growing field of new materials, especially one- and two-dimensional materials, nanostructured materials and the associated topological effects

The symbiosis of these three areas will give birth to revolutionary concepts such as nanoarchitectronics (the science and technology for building extreme multiscale systems covering from nanometer to mesoscopic scales) and artificial nano-engineered interfaces.

Acknowledgements

The authors would like to acknowledge the SHT company for providing MW CNT bundles.

Author details

Charlotte Tripon-Canseliet[1]* and Jean Chazelas[2]

*Address all correspondence to: charlotte.tripon-canseliet@espci.fr

1 LPEM, ESPCI Paris, PSL Research University, CNRS, Sorbonne Université, Paris, France

2 THALES DMS, Elancourt, France

References

[1] Esconjauregui S, Fouquet M, Bayer BC, Ducati C, Smajda R, et al. Growth of Ultrahigh Density Vertically Aligned Carbon Nanotube Forests for Interconnects. ACS Nano. 2010;**4**: 7431-7436

[2] Teo KBK, Chhowalla M, Amaratunga GAJ, Milne WI, Hasko DG, Pirio G, Legagneux P, Wyczisk F, Pribat D. Uniform patterned growth of carbon nanotubes without surface carbon. Applied Physics Letters. 2001;**79**:1534-1536

[3] Chhowalla M, Teo KBK, Ducati C, Rupesinghe NL, Amaratunga GAJ, Ferrari AC, Roy D, Robertson J, Milne WI. Growth process conditions of vertically aligned carbon nanotubes using plasma enhanced chemical vapor deposition. Journal of Applied Physics. 2001;**90**: 5308-5317

[4] Lee SW, Lee DS, Morjan RE, Jhang SH, Sveningsson M, Nerushev OA, Park YW, Campbell. A Three-Terminal Carbon Nanorelay. Nano Letters. 2004;**4**:2027-2030

[5] Kang J et al. Computational study of metal contact to monolayer TMD semiconductors. Physical Review X. 2014;**4**:031005

[6] Leonard F. Electrical contacts to one and two-dimensional nanomaterials. Nature Nanotechnology. 2011;**6**:773-783

[7] Allain A et al. Electrical contacts to two-dimensional semiconductors. Nature Materials. 2015;**14**:1195-1205

[8] McEuen PL, Fuhrer MS, Park H. Single-walled carbon nanotube electronics. IEEE Transactions on Nanotechnology. Mar. 2002;**1**(1):78-85

[9] Zolper JC. Status, challenges, and future opportunities for compound semiconductor electronics. In: 25th Annual Gallium Arsenide Integrated Circuits Symposium. pp. 3-6; 2003

[10] Burke PJ. AC performance of nanoelectronics: Towards a THz nanotube transistor. Solid State Electronics. 2004;**40**:1981

[11] Xing CJ et al. Investigation on self-heating effect in carbon nanotubes field-effect transistors. IEEE Transaction on Electron Devices. 2010;**58**:523

[12] Kim S. et al. A poly-Si gate carbon nanotube field effect transistor for high frequency applications. IEEE Intern. Microwave Symposium. 2005:303-306

[13] Narita et al. RF performances of multiple channel carbon nanotube transistors, Trends in Nanotechnology Conference, Grenoble. 2006

[14] Le Louarn A et al. Intrinsic current gain cutoff frequency of 30 GHz with CN transistors. Applied Physics Letters. 2007;**90**:233108

[15] Keshavarzi A et al. Carbon Nanotube Field-Effect Transistors for High- Performance Digital Circuits—Transient Analysis, Parasitics, and Scalability. IEEE Transactions on Electron Devices. 2006;**53**(11):2718-2726

[16] Pesetski A et al. Carbon nanotube field-effect transistor operation at microwave frequencies. Applied Physics Letters. 2006;**88**:113103

[17] Wang QH, Kalantar-Zadeh K, Kis A, Coleman JN, Strano MS. Electronics and optoelectronics of two-dimensional transition metal dichalcogenides. Nature Nanotechnology. 2012;**7**:699-712

[18] Jariwala D, Sangwan VK, Lauhon LJ, Marks TJ, Hersam MC. Emerging device applications for semiconducting two-dimensional transition metal dichalcogenides. ACS Nano. 2014;**8**:1102-1120

[19] Cheng R, Jiang S, Chen Y, Liu Y, Weiss N, Cheng H-C, Wu H, Huang Y, Duan X. Few-layer molybdenum disulfide transistors and circuits for high-flexible electronics. Nature Communications. 2014;**5**:5143

[20] Tong X, Ashalley E, Lin F, Li H, Wang ZM. Advances in MoS2-based field effect transistors (FETs). Nano-Micro Letters. 2015;**7**:203-218

[21] Lau JH. Overview and outlook of through-silicon via (TSV) and 3D integrations. Micro-Electronics International. May 2011;**28**(2):8-22

[22] Ramm P et al. 3D integration technology: Status and application development. In: 2010 Proceedings of the ESSCIRC; 2010. pp. 9-16

[23] Carson FP, Kim YC, Yoon IS. 3-D stacked package technology and trends. Proceedings of the IEEE. Jan. 2009;**97**(1):31-42

[24] Motoyoshi M. Through-silicon via (TSV). Proceedings of the IEEE. Jan. 2009;**97**(1):43-48

[25] Dong M, Santagata F, Sokolovskij R, Wei J, Yuan C, Zhang G. 3D system-in-package design using stacked silicon submount technology. MicroElectronics International. Apr. 2015;**32**(2):63-72

[26] Santagata F et al. Fully back-end TSV process by cu electro-less plating for 3D smart sensor systems. Journal of Micromechanics and Microengineering. May 2013;**23**(5):55014

[27] Lu JJ-Q, Cale TS, Gutmann RJ. Rensselaer 3D integration processes. In: Garrou P, Bower C, Ramm P, editors. Handbook of 3D Integration. Wiley-VCH, Weinheim. Vol. 11. 2008. pp. 447-462

[28] Kikuchi H et al. Tungsten through-silicon via technology for three-dimensional LSIs. Japanese Journal of Applied Physics. Apr. 2008;**47**(4S):2801

[29] Wolf MJ et al. High aspect ratio TSV copper filling with different seed layers. In: Electronic Components and Technology Conference, 2008. ECTC. 58th ed; 2008. pp. 563-570

[30] Horváth B, Kawakita J, Chikyow T. Through silicon via filling methods with metal/polymer composite for three-dimensional LSI. Japanese Journal of Applied Physics. Jun. 2014; **53**:6S

[31] Selvanayagam CS, Lau JH, Zhang X, Seah SKW, Vaidyanathan K, Chai TC. Nonlinear thermal stress/strain analyses of copper filled TSV (through silicon via) and their flip-chip microbumps. IEEE Transactions on Advanced Packaging. Nov. 2009;**32**(4):720-728

[32] Gupta T. Copper Interconnect Technology. New York, NY : Springer Science+Business Media, LLC. 2009

[33] Gu C, Xu H, Zhang T-Y. Fabrication of high aspect ratio through-wafer copper interconnects by reverse pulse electroplating. Journal of Micromechanics and Microengineering. Jun. 2009;**19**(6):65011

[34] Naeemi A, Meindl JD. Performance modeling for single- and multiwall carbon nanotubes as signal and power interconnects in Gigascale systems. IEEE Transactions on Electron Devices. Oct. 2008;**55**(10):2574-2582

[35] Naeemi A, Meindl JD. Physical modeling of temperature coefficient of resistance for single- and multi-wall carbon nanotube interconnects. IEEE Electron Device Letters. Feb. 2007;**28**(2):135-138

[36] Li H, Banerjee K. High-frequency analysis of carbon nanotube interconnects and implications for on-chip inductor design. IEEE Transactions on Electron Devices. Oct. 2009;**56**(10): 2202-2214

[37] Kajiura H, Nandyala A, Bezryadin A. Quasi-ballistic electron transport in as-produced and annealed multiwall carbon nanotubes. Carbon. May 2005;**43**(6):1317-1319

[38] Hanson GW. Dyadic Green's functions and guided surface waves for a surface conductivity model of graphene. Journal of Applied Physics. 2008;**103**:064302. DOI: 10.1063/1.2891452

[39] Hao J, Hanson G. Optical scattering from a planar array of finite-length metallic carbon nanotubes. Physical Review B. Apr. 2007;**75**(165416):1-7

[40] Maksimenko S, Slepyan G, Nemilentsau A, Shuba M. Carbon nanotube antenna: Far-field, near-field and thermal-noise properties. Physica E. 2008;**40**:2360-2364

[41] Berres J, Hanson G. Multiwall carbon nanotubes at RF-THz frequencies: Scattering, shielding, effective conductivity, and power dissipation. IEEE Transactions on Antennas and Propagation. Aug. 2011;**59**(8):3098-3103

[42] Choi S, Sarabandi K. Performance assessment of bundled carbon nanotube for antenna applications at terahertz frequencies and higher. IEEE Transactions on Antennas and Propagation. Mar. 2011;**59**(3):802-809

[43] Vincenzi et al. Open-thru de-embedding for graphene RF devices. IEEE IMS 2014. Jun. 2014. DOI: 10.1109/MWSYM.2014.6848457

[44] Quéré Y. Physique des matériaux. Collection Ellipses. ISBN: 2729888586

[45] Tripon-Canseliet C, Xavier S, Modreanu M, Ziaei A, Chazelas J. Vertically-grown MW CNT bundles microwave characterization for antenna applications. In: IEEE Conference on Numerical Electromagnetic Modeling and Optimization for RF, Microwave and Terahertz Applications (NEMO), Pavia, Italie; 2014

[46] Tripon-Canseliet C, Xavier S, Deligeorgis G, Coccetti F, Ziaei A, Modreanu M, Chazelas J. Electromagnetic modelling of MW CNT bundles from microwave characterization: Application to small microwave antenna design in integrated technology. In: IEEE European Microwave Conference, Special Workshop on Advances in the "Carbon Based Smart System for Wireless Application", Rome, Italy; 2014